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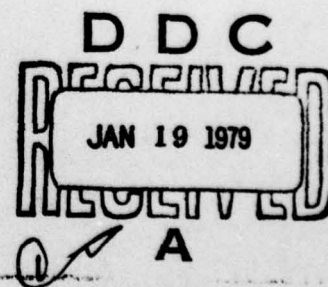COMBUSTION INSTABILITY TESTING
OF NASA BSM PROPELLANT (UTP 19048)
IN THE NWC T-BURNER

by

James E. Crump

Research Department

August 1976

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This work is a portion of the effort to determine the combustion stability of the NASA Booster Separation Motor (BSM) while the motor is in the early development stage. The motor is being developed by the Chemical Systems Division of United Technology Corporation (CSD/UTC); motor stability work is being carried out by CSD/UTC, the Air Force Rocket Propulsion Laboratory (RPL), and the Naval Weapons Center (NWC). This report describes the T-burner testing and results obtained at NWC on the unstable combustion characteristics of the BSM propellant.

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FOREWORD

This report contains the results of a portion of the NWC effort to
determine the combustion stability of the solid rocket motors being
developed for the NASA Space Shuttle. In particular, this report gives
the results obtained from the combustion stability testing of the Booster
Separation Motor (BSM) propellant.

The work was performed by the Naval Weapons Center during the period
February-July 1976, for the MArshall Space Flight Center under NASA
Order H151468.

This report has been prepared primarily for timely presentation of
information and is released at the working level.

<div style="text-align:right">

R. L. Derr
Head, Aerothermochemistry Division
Research Department
10 August 1976

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CONTENTS

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INTRODUCTION

The work is a portion of the effort to determine the combustion stability of the NASA Booster Separation Motor (BSM) while the motor is in the early development stage. The motor is being developed by the Chemical Systems Division of United Technology Corporation (CSD/UTC); motor stability work is being carried out by CSD/UTC, the Air Force Rocket Propulsion Laboratory (RPL), and the Naval Weapons Center (NWC). This report describes the T-burner testing and results obtained at NWC on the unstable combustion characteristics of the BSM propellant (UTP 19048).

Approximately 16 pounds (7.2 kilograms) of UTP 19048 propellant from Batch 400-1429 was received from CSD/UTC by NWC on 28 January 1976.

EXPERIMENTAL METHOD

The NWC medium frequency range, 1.5-inch (3.75 cm) diameter, center vented T-burner was used for measuring the pressure-coupled combustion instability behavior of the propellant. A simple analysis of the internal geometry of the BSM indicated a frequency of 900 Hz for the first longitudinal mode of the cavity and a frequency of 2,100 and 3,200 Hz for the first and second tangential modes. Hence, T-burner tests were performed over the frequency range of 850-3,300 Hz and at the approximate operating pressure of the motor, 1,600 psi (11.2 MPa).

Initial testing of the propellant in the T-burner indicated that the propellant/burner system was stable; i.e., pressure oscillations did not grow spontaneously. Hence, the NWC pulsed during burn/after burn (DB/AB) technique[1] was used for the test program. A slight, but very important, variation in the DB/AB technique was used for the AB pulse for this test series. The decay of the AB pulse was of a relatively low rate. As a result, the technique of firing pulses at various times after burnout in order to determine AB damping was not useable since each pulse decay occupied a long period of time relative to the time for the burner pressure to drop to the surge tank pressure. To overcome

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[1]Naval Weapons Center. *Oscillatory Combustion Experimentation and Analysis Work in Support of an Air Force Program 1971-1972*, by J. E. Crump, et.al. China Lake, Calif., NWC, June 1974. (NWC TP 5630, publication UNCLASSIFIED.)

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this difficulty, the AB pulse was fired in the latter portion of burning at a time such that the oscillations would decay to 14-21 kPa (2-3 psi) at burnout. A plot of the pressure amplitude versus time for decay associated with a typical test is shown in Figure 1 with the approximate time of burnout indicated. As can be seen, the slope of the data gradually increases as burning (combustion driving) decreases. Following web burnout, the rate of decay attains a constant value. This linear portion of the data after burnout was taken to be indicative of the after burnout damping value. This technique was used on all the tests of UTP 19048 propellant reported here.

T-burner tests were run using flat propellant samples (Figure 2a with an area ratio (S_{be}/S_{co}) of 0.9/1); 15 out of 17 tests provided useful data. Tests were also run using cylindrical samples (Figure 2b) with an area ratio of 0.9/1; the pulse during burning was fired at approximately the "flush" condition of propellant burning surface and chamber wall. Eight out of nine tests provided useful data. Due to the lack of agreement of data between NWC, RPL, and CSD/UTC, the remaining propellant was used to obtain data using the variable area technique (similar to that used by CSD/UTC and RPL) at area ratios of 0.4/1, 0.9/1, and 1.4/1. Eleven out of twelve tests provided useful data.
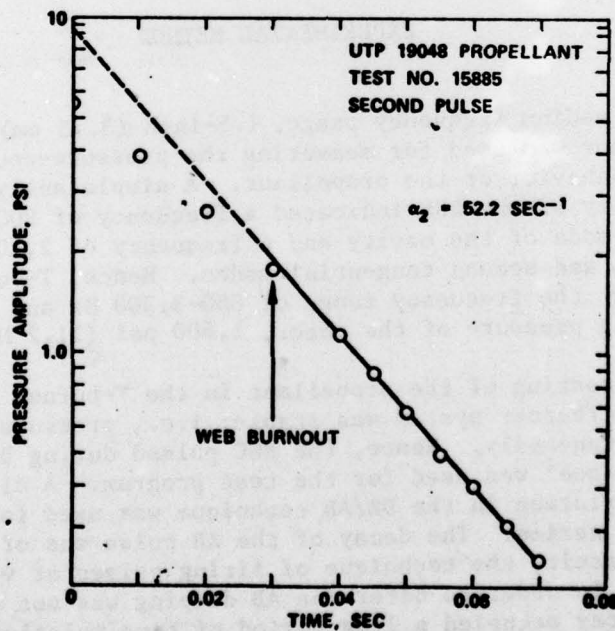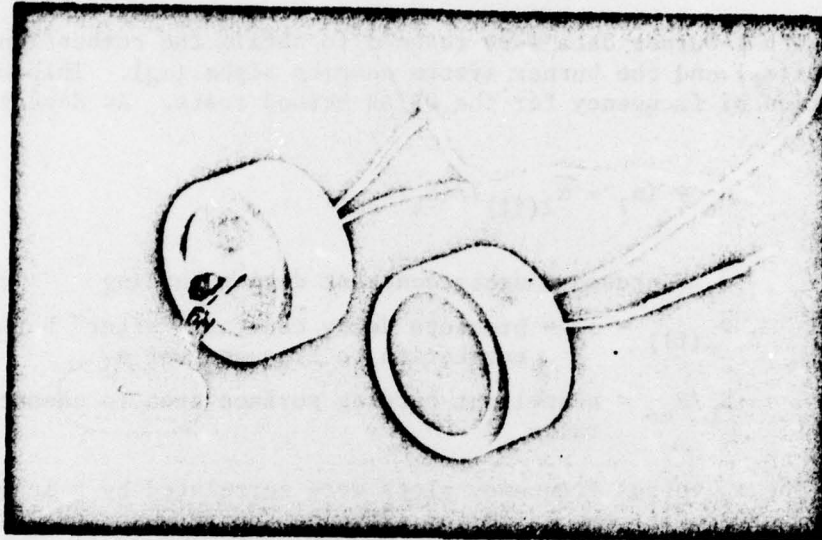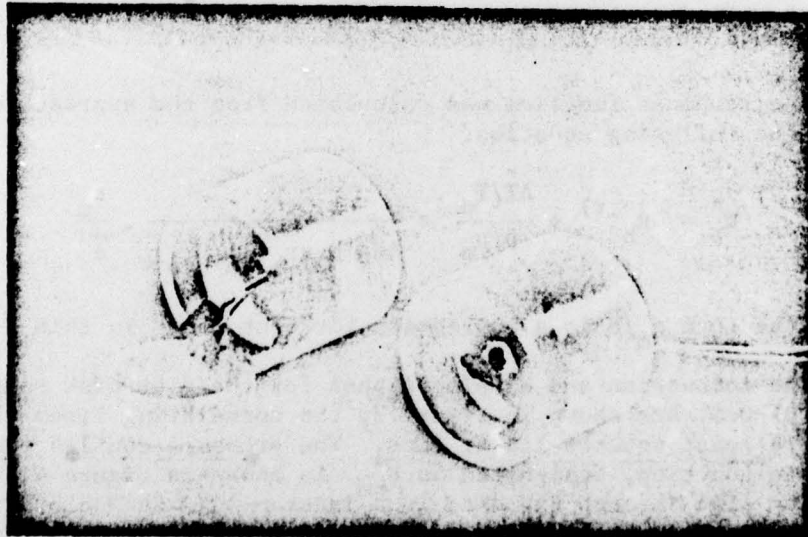

FIGURE 1. Representative Second Pulse Decay.

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a. Flat Propellant Sample.

b. Cylindrical Propellant Sample.

FIGURE 2. Propellant Configuration and Sample
Holder Assemblies.

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RESULTS

The T-burner data were reduced to obtain the combustion driving alpha (α_c) and the burner system damping alpha (α_d). This was done as a function of frequency for the DB/AB method tests. As described in Ref. 1,

$$\alpha_c = (\alpha_1 - \overline{\alpha}_{2(f1)})/(S_b/S_{co}) \tag{1}$$

where

α_1 = pressure decay constant during burning

$\overline{\alpha}_{2(f1)} = \alpha_d$ = pressure decay constant "after" burning with correction to frequency of α_1

S_b/S_{co} = propellant burning surface area to channel area ratio

The α_c versus frequency plots were correlated by a least squares second order fit; the α_d versus frequency curve was correlated by a least squares first order fit forced through zero.

The above information along with the burner length and propellant properties were used to calculate the propellant response function assuming that the effect of flow at the vent was negligible and in the case of cylindrical samples, that there was no significant flow turning effect.

The response function was calculated from the approach of Culick[2] using the following equation.

$$R_b^* = R_b(r) + \frac{\widehat{\Delta T/T_o}}{\hat{p}/P_o} = \frac{\alpha_c \overline{p}}{4f\overline{a} \, \rho_p \, \overline{r}_b (S_b/S_{co})} \cdot \frac{a_m}{\overline{a}} \tag{2}$$

where the term $a_m/\overline{a}$ is a correction for heat loss[3] in this T-burner.

The combustion and damping alphas for the flat disk samples (area ratio of 0.9) are shown in Figure 3; the correlating lines through the data are least squares linear fits. The pressure-coupled propellant response function, designated as R_{be}^*, is shown in Figure 4; the correlating line through the data is a least squares second order fit which was forced through the value of n, the propellant burning rate exponent, at zero frequency as suggested by theory.

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[2]Air Force Rocket Propulsion Laboratory. *T-Burner Testing of Metallized Solid Propellants*, by F. E. C. Culick. Edwards, Calif., AFRPL, October 1974. (AFRPL-TR-74-28, publication UNCLASSIFIED.)

[3]George L. Dehority and H. B. Mathes, "Acoustic Response Function Equation for a T-Bruner with High Heat Loss". *AIAA Journal*, Vol. 6, No. 4, April 1968, pp. 741-742.
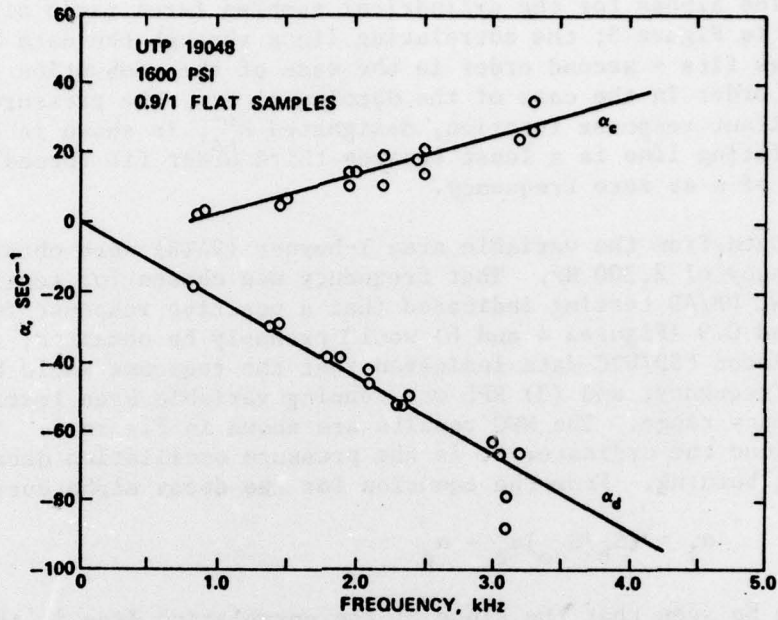
FIGURE 3. Combustion and Damping Alphas for
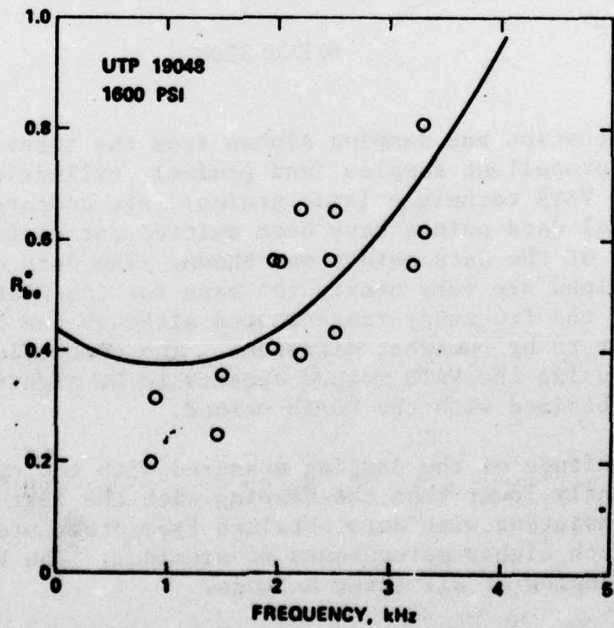0.9/1 Area Ratio Flat Samples.

FIGURE 4. Response Function From
Flat (End Burning) Samples.

The alphas for the cylindrical samples (area ratio of 0.9) are shown in Figure 5; the correlating lines through the data are least squares fits - second order in the case of the combustion alpha and first order in the case of the damping alpha. The pressure-coupled propellant response function, designated R^*_{bs}, is shown in Figure 6; the correlating line is a least squares third order fit forced through the value of n at zero frequency.

Data from the variable area T-burner (VATB) were obtained at a frequency of 2,200 Hz. That frequency was chosen for testing because (1) NWC DB/AB testing indicated that a positive response function between 0.5 and 0.9 (Figures 4 and 6) would probably be obtained, (2) the extrapolated CSD/UTC data indicated that the response would be negative at that frequency, and (3) RPL was running variable area tests in that frequency range. The NWC results are shown in Figure 7. In the VATB technique the ordinate, α, is the pressure oscillation decay measured during burning. From the equation for the decay alpha during burning

$$\alpha_1 = (S_b/S_{co})\alpha_c - \alpha_d \tag{3}$$

it can be seen that the slope of the correlating line is the combustion alpha (α_c) and the intercept (area ratio of zero) is the system damping (α_d). As noted in Figure 7, the results (at 2,200 Hz) were a combustion alpha of 9.54 sec^{-1} and a damping alpha of 33.65 sec^{-1}. The value of the propellant response function calculated from the data was 0.255.

DISCUSSION

The combustion and damping alphas from the three sets of T-burner tests, flat propellant samples (end grains), cylindrical samples (side grains), and VATB technique (side grains), are compared in Figure 8. The individual data points have been omitted for clarity; the least squares fits of the data points are shown. The data obtained for the combustion alpha are very nearly the same for the flat and the cylindrical samples over the frequency range tested although the trends with frequency appear to be somewhat different. The combustion alpha obtained at 2,200 Hz using the VATB method appears to be significantly lower than the values obtained with the DB/AB method.

The magnitude of the damping measured with the cylindrical samples is significantly lower than the damping with the flat samples. This result is consistent with data obtained from other propellant systems containing much higher percentages of aluminum. The VATB method gave the lowest damping of all three methods.
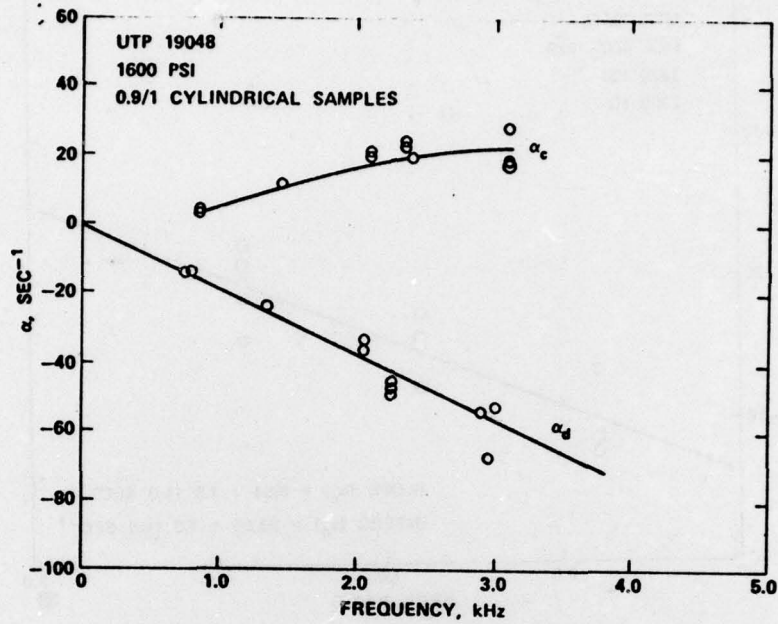
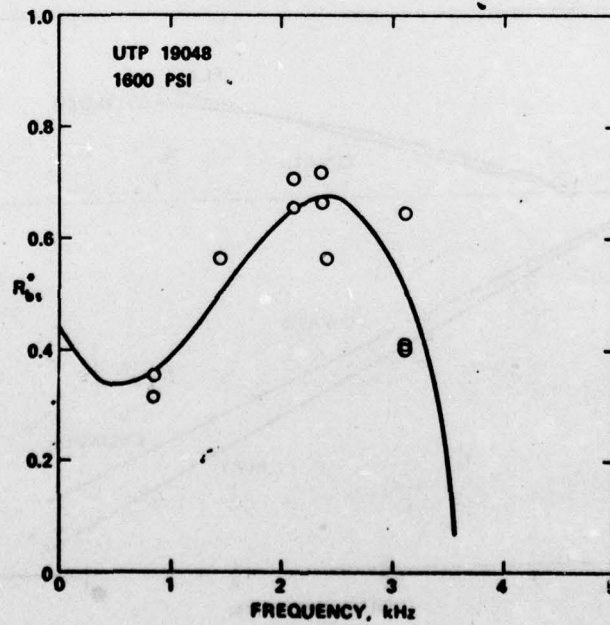FIGURE 5. Combustion and Damping Alphas for 0.9/1 Area Ratio Cylindrical Samples.

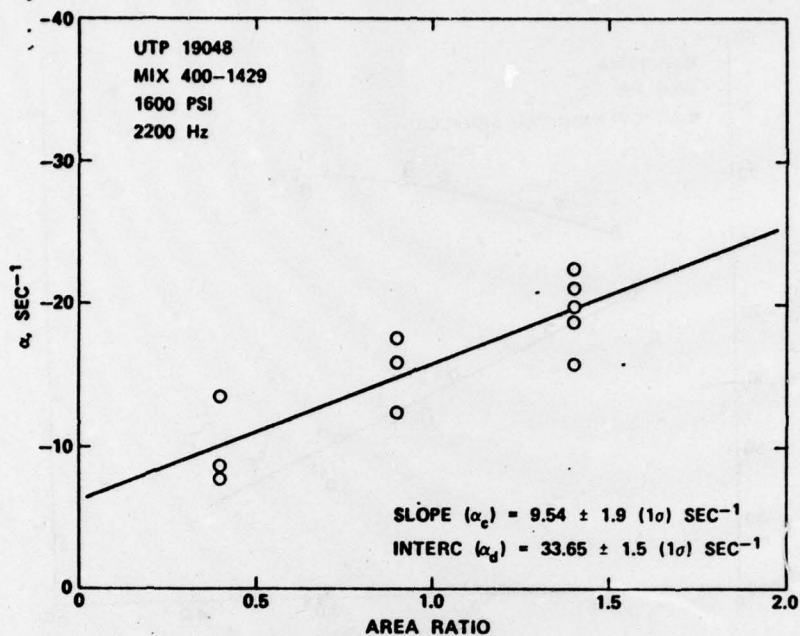FIGURE 6. Response Function From Cylindrical (Side Burning) Samples.

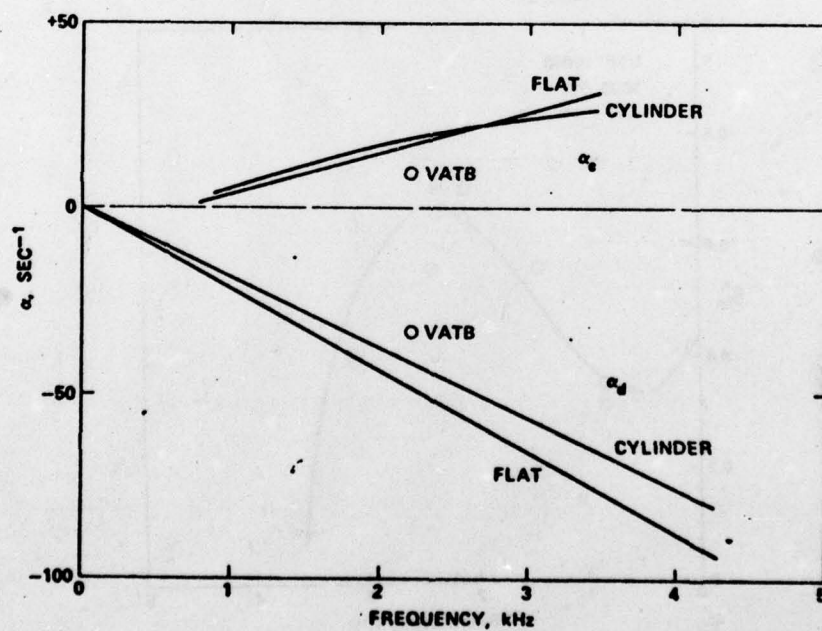**FIGURE 7.** Combustion and Damping Alphas From VATB Tests.

FIGURE 8. Comparison of Combustion and Damping Alphas for the Three Test Sets.

The propellant response functions obtained for the three sets of tests are shown in Figure 9. For clarity, only the fitted curves are shown. As pointed out above, a second order fit was used for the end sample data and a third order fit for the side sample data. These curves gave the best simple fit to the data over the range of conditions tested. Obviously, a fit utilizing the functional form of Culick[4] would have been more in line with current theory; however, the large scatter and general trend of the R_b^* data did not seem to justify the more complicated (and expensive) approach. With the fitting procedure used, however, it is obvious that the R_b^* data are inconsistent above 3 kHz.

It is rather difficult to understand how the response functions differed considerably in both magnitude and trend with frequency, although the combustion alphas for the end and side propellant samples were quite similar in value. Part of the difference in magnitude is due to the differences in burning rate of the propellant in the two different configurations. The end samples had an average burning rate of 0.814 in/s (20.7 mm/s) while the side samples had a rate of 0.842 in/s (21.4 mm/s). The differences in rate are probably due in part to the differences in heat loss from the two configurations.

The response function determined by the VATB method at 2,200 Hz was considerably lower than that obtained from the side burning samples. Considering that the VATB method used side burning samples, one would expect better agreement between R_{bs}^* from the DB/AB method and R_{bs}^* from the VATB method. However, this was not the case.

The lack of consistency in the response function as measured by the three sets of NWC T-burner tests and also the lack of reasonable agreement between the NWC, CSD/UTC, and RPL data unfortunately points out again that determination of propellant response function is not well in hand.

At frequencies above 1,200 Hz the response functions for UTP 19048 propellant determined by NWC were higher than those obtained by CSD/UTC and RPL. As a result the NWC data are being used to calculate the "worst case" conditions for the motor stability of the BSM.

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[4] American Institute of Aeronautics and Astronautics. "A Review of Calculations for Unsteady Burning of a Solid Propellant," by F. E. C. Culick. *AIAA Journal*, Vol. 6, No. 12, December 1968, pp. 2241-55. (Publication UNCLASSIFIED.)
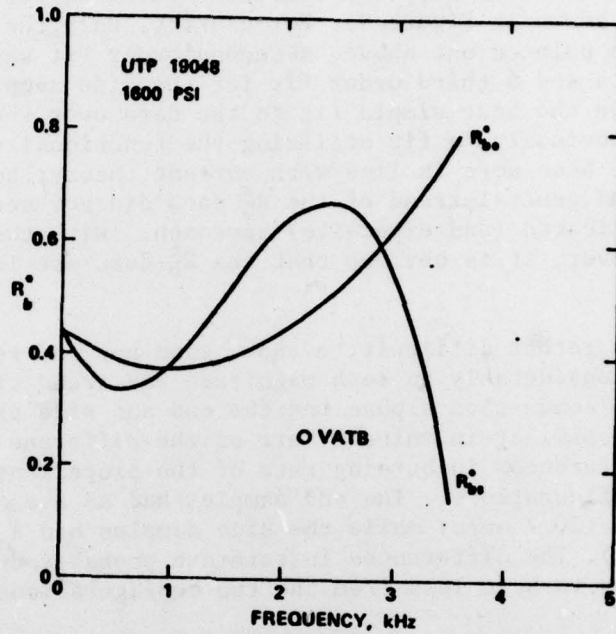
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FIGURE 9. Comparison of the Combustion Response Function for the Three Test Sets.